SUBSTITUTE SPECIFICATION

APPARATUS AND METHOD FOR CHARGING AND DISCHARGING A CAPACITOR TO A PREDETERMINED SETPOINT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. Provisional Application No. 60/408,468 filed on September 5, 2002 which is incorporated by reference herein. This application is related to U.S. Patent Application No. 10/621,797 filed on July 17, 2003 for an Apparatus and Method for Charging and Discharging a Capacitor.

FIELD OF THE INVENTION

[0002] The present invention relates to electronic methods and circuits for controlling proportional general purpose, smart material-based actuators.

BACKGROUND OF THE INVENTION

[0003] Actuator technologies are being developed for a wide range of applications. One example includes a mechanically-leveraged smart material actuator that changes shape in response to electrical stimulus. This change in shape is proportional to the input voltage. Since this shape change can be effectuated predominantly along a single axis, such actuators can be used to perform work on associated mechanical systems including a lever in combination with some main support structure. Changes in axial displacement are magnified by the lever to create an actuator with a useful amount of force and displacement. Such force and displacement is useful for general-purpose industrial valves, clamps, beverage dispensers, compressors or pumps, brakes, door locks, electric relays, circuit breakers, and other applications actuated by means including solenoids, motors or motors combined with various transmission means. Smart materials, however, and piezoelectric materials specifically, can require hundreds of volts to actuate and cause displacement. This type of voltage may not be readily available and may have to be derived from a lower voltage as one would find with a battery.

[0004] Another characteristic of piezoelectric materials is that the materials are capacitive in nature. Moreover, a single actuator is often controlled using three separate signals: a control signal, a main supply and a ground.

SUMMARY OF THE INVENTION

[0005] An apparatus for charging and discharging a capacitor to predetermined setpoints includes a smart material actuator and a voltage controlled direct current (DC) to DC converter for operating the smart material actuator in a proportional manner. The voltage controlled DC to DC converter can further include a self-oscillating drive circuit connected to a primary coil of a transformer with push-pull drive signals 180 degrees out of phase. The voltage controlled DC to DC converter can also include an auxiliary coil on the transformer. An attached diode rectifier to generate a DC voltage from an AC signal of the secondary coil on the transformer can also be included with the DC to DC converter as well as a voltage feedback network for voltage regulation.

[0006] The voltage controlled DC to DC converter can further include control circuitry for stopping and starting the self-oscillating mechanism and can also feature a diode on an input stage for reverse polarity protection. Moreover, the control circuitry can further include a bead inductor and bypass capacitor for suppression of radiated EMI into the power source of the system.

[0007] Another feature of the invention includes a smart material drive circuit for actively charging and discharging the smart material actuator in response to connecting and disconnecting a power source, respectively. The drive circuit for actively controlling at least one of charging and discharging the smart material actuator can be responsive to a control signal.

[0008] Yet another embodiment of the invention for charging and discharging a capacitor to predetermined setpoints includes a smart material actuator, a power source connectible to the smart material actuator, and a switch circuit for actively discharging the smart material actuator in response to removal of the connection to the power source. The switch circuit for actively charging the smart material actuator can further be responsive to connecting the power source or a control signal input. The switch circuit can actively control at least one of charging and discharging the smart material actuator in response to a control signal and can further include a voltage comparator and field effect transistor (FET) to control the DC to DC converter. The switch can, according to the invention, have three

operational modes, charge load, hold load and discharge load. Hence, the method for charging and discharging a capacitor to predetermined setpoints according to the present invention includes the steps of providing a smart material actuator and operating the smart material actuator in a proportional manner with a voltage controlled DC to DC converter. An alternative method for charging and discharging a capacitor to predetermined setpoints according to the invention includes the steps of providing a smart material actuator, connecting a power source to the smart material actuator, and actively discharging the smart material actuator in response to removal of the connection to the power source with a switch circuit.

[0009] With the use of electronic design and simulation software and electronic prototyping of the circuit, details for using a minimum number of components while maintaining a cost-effective, and low power solution are realized. This electronic subsystem, when coupled to a mechanically-leveraged smart material actuator, creates a commercially viable proportional actuator solution for general purposes and industrial applications.

[0010] Other applications of the present invention will become apparent to those skilled in the art when the following description of the best mode contemplated for practicing the invention is read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The description herein makes reference to the accompanying drawings wherein like reference numerals refer to like parts throughout the several views, and wherein:

[0012] Fig. 1 is an electronic schematic of a voltage controlled DC to DC converter with active regulation to which the present invention is applied;

[0013] Fig. 2 is an electronic schematic of a DC to DC converter of the present invention;

[0014] Fig. 3 is an electronic schematic of the electronic switch of the present invention illustrating current flow when the switch is closed;

[0015] Fig. 4 is an electronic schematic of the electronic switch of the present invention illustrating current flow when the switch is open; and

[0016] Fig. 5 is an electronic schematic of the control circuit of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0017] Figure 1 shows an electronic schematic of a system 10 for controlling a proportional mechanically leveraged smart material actuator (shown as capacitor 54) including a specialized power source 12 coupled to switching circuitry 44 and control circuitry 64.

[0018] According to the preferred embodiment, the system 10 of Figure 1 is a DC to DC converter, switching circuit, and control circuit operative either to supply a variable stimulating voltage or to actively discharge the actuator. As best shown in Figure 2, the DC to DC converter 12 includes a supply voltage 14 connected to a bead inductor 16 in series with a reverse protection diode 18. Bead inductor 16 acts as a filter to remove noise generated by the collector of negative positive negative (NPN) transistor 20 connected to the supply voltage 14. NPN transistor 20 and NPN transistor 22 form a push-pull driver for transformer 24. Resistors 26, 28, 30 and 32 form resistive voltage dividers and set the basic bias points for NPN transistors 20 and 22.

[0019] Transformer 24 is wound not only with a primary coil 24a and a secondary coil 24b, but also with an auxiliary coil 24c. Auxiliary winding 24c resistors 34, 36, 28, and capacitors 38, 40 form feedback means to cause oscillation on the base of NPN transistors 20, 22. Oscillation is 180 degrees out of phase between the two NPN transistors 20, 22, forming a self-oscillating push-pull transformer driver. The secondary coil 24b of transformer 24 is connected to a rectifier in the form diode 42. It should be noted that when the base of transistor 22 is grounded, the self-oscillating mechanism is stopped. When the ground is removed, the self-oscillating mechanism is restarted. As shown in Figure 1, switch circuitry 44, when commanded, is capable of actively controlling the voltage to the capactitive load.

[0020] Control circuitry 64 monitors the control voltage and output voltage and makes the decision to turn on the DC to DC converter, or turn on the discharge

switch, or hold the current voltage level at the capacitive load. Included in the system is means for forcing the load to ground should the supply voltage be removed.

[0021] Referring now to Figure 3, switching circuitry 44 is depicted isolated from the schematic of Figure 1 to better illustrate the operative features of the switching circuitry 44 when it is closed. When switch 48 is closed, current flows from a power source 50 through switch 48 and through bead inductor 52, charging the capacitive load 54. Also, current flows into resistive voltage divider 56 driving the NPN transistor 58 on, which turns NPN Darlington pair 60 off. The rate of charge is determined by the impedance of the power source 50 and the capacitance of the load 54. Resistor 62 and NPN transistor 58 serve as a level translator between the switched power and control signal, so the switched power and control signal do not have to have the same voltage levels.

[0022] Referring now to Figure 4, the current flow in switching circuitry 44 is shown when switch 48 is open. When switch 48 is open, no current flows from the power source 50. Also, current flows into resistive voltage divider 56 through switch 48 to ground, driving the NPN transistor 58 off. This turns NPN Darlington pair 60 on, causing current flow through resistor 46 and discharging capacitive load 54. The rate of discharge is determined by the value of resistor 46 and capacitive load 54. Resistor 62 and NPN transistor 58 serve as a level translator between the switched power and control signal so the switched power and control signal do not have to have the same voltage levels.

[0023] Referring now to Figure 5, the control circuit 64 of Figure 1 is shown isolated to better illustrate the operative features of the circuit 64. Analog control voltage flows through resistor 66 and is clamped by Zener diode 68 at a preset voltage so as not to damage the input of operational amplifier 70. Further, resistor 66 is part of resistive voltage divider network 72. The network 72 provides two voltages; one voltage is the reference to shut the DC to DC converter 12 down, the other, a reference to actively discharge the capacitive load. Operational amplifier 70 is used in a voltage comparator mode that is associated with the DC to DC converter 12 shutdown mode. Operational amplifier 74 is used in a voltage comparator mode and is associated with the active discharge mode. Resistors 76, 78, 80 form a second

resistive voltage divider network. This network monitors the capacitive load voltage and derives the voltages that operational amplifiers 70, 74 compare to the reference voltages derived from resistors 66, 72. When the voltage at the non-inverting terminal of operational amplifier 70 is greater than the voltage at the inverting terminal, the output of the amplifier goes to the positive saturation state, turning FET transistor 82 on and causing the DC to DC converter to stop.

[0024] When the voltage at the inverting terminal of operational amplifier 70 is greater than that at the non-inverting terminal, the output of the amplifier goes to the negative saturation state, turning FET transistor 82 off and causing the DC to DC converter to run. When the voltage at the non-inverting terminal of operational amplifier 74 is greater than that at the inverting terminal the output of the amplifier goes to the positive saturation state, turning FET transistor 84 on and causing the active discharge of capacitive load. When the voltage at the inverting terminal of operational amplifier 74 is greater than the voltage at the non-inverting terminal, the output of the amplifier goes to the negative saturation state, turning FET transistor 84 off. In this system there are three distinct states, (1) DC to DC converter on and capacitive load discharge switch open, (2) DC to DC converter off and capacitive load discharge switch open, and (3) DC to DC converter off and capacitive load discharge switch closed.

[0025] In the embodiment illustrated in Figures 1, 2, 3, 4, and 5,the components have been chosen for their current carrying ability, voltage rating, and type. Other suitable components can include FET small signal, and power transistors, wire wound, thin film, and carbon comp resistors, ceramic, tantalum, and film capacitors, or any combination of suitable components commonly used for high volume production. Although these materials given as examples provide excellent performance, depending on the requirements of an application, use of other combinations of components can be appropriate. Likewise, the embodiment illustrates components that are commercially available.

[0026] While the invention has been described in conjunction with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment but, on

the contrary, it is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims, which scope is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures as permitted under law.